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Computational aspects of MN activity estimation: a case study with post-stroke subjects

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***Abstract*— Spinal circuits play an important role in the generation of rhythmic motor activity, intermediating between descending signals and peripheral sensory information. The study of these circuits can provide a better understanding of the control mechanisms during the execution of cyclic motor tasks in healthy subjects or in patients with motor deficits due to a neurological disease. This work shows preliminary results regarding the estimation of spinal cord activity of post-stroke subjects obtained from the EMG signals by improving the computational model. This new model allows a better quantitative evaluation of motor performance in clinical contexts.**

Keywords- computation and evaluation of spinal cord activity; locomotion; motor control; stroke.

I. Introduction

Many authors have hypothesized that neural circuits located in the spinal cord drive muscular activation while intermediating between descending signals and peripheral sensory information [1-3]. For instance, it was observed that some spinal circuits have the potential to generate rhythmic motor activity able to sustain locomotion in decerebrated cats while walking on treadmill [4], and, when suitably stimulated, they allow rats with spinal cord injury to achieve stepping motor tasks [5]. These spinal circuits are supposed to provide the major input to motoneurons leading muscular activity during locomotion [6], reducing the computational complexity of the motor control system while managing the huge amount of redundant involved actuators.

The analysis of motoneuronal (MN) activity during the execution of motor tasks, like walking, can be a valuable support to understand mechanisms leading to muscular recruitment and motor control strategies. In particular, it can be useful in a clinical context to study mechanisms of neuromotor recovery in patients with spinal cord injury or post-stroke subjects and to plan personalized and more effective rehabilitation interventions. In this regard, it has been already shown that MN activity reflects the synergic enrollment of muscles during locomotion [7] and it has hypothesized that neuro-rehabilitative treatments after stroke should be focused on recovery of those synergies which activation patterns are altered by the trauma [8].

Unfortunately, it is difficult to study spinal activity during locomotion by using current imaging techniques. Indeed, they allow to obtain anatomical and functional information of spinal cord structures only during the execution of isometric or small movements of distal parts of the body in order to avoid artifacts due to the movement of the body.

To overcome these limitations, previous authors have proposed an alternative representation of MN activity approximated along the rostrocaudal direction on both cats [9] and humans [7]. Briefly, since each spinal segment innervates several muscles, MN activity was estimated by a weighted summation of electromyographic (EMG) signals of all muscles innervated by that spinal segment [7, 9]. The main assumption underlying such representation is that EMG signals, after full-wave rectifying and filtering, can provide an indirect measure of the net MN firing rate.

It was shown that spinal maps estimated as described above are sensitive to different gaits [7, 10, 11], external constraints like walking on slippery surface [12], aging [13], and neuro-pathologies like spinal cord injury. In this regard, Grasso and colleagues [14] observed that after a spinal lesion, the spinal networks can be reorganized involving both supralesional and sublesional segments, extending from the cervical to the sacral sections.

Spinal maps have never been applied to investigate walking in post-stroke subjects. In particular, we expect that they can be useful to investigate the motor control strategies aimed at managing affected and unaffected sides after the trauma.

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In this paper we show preliminary results concerning the estimation of spinal activity in post-stroke patients, by using a modified version of the methodology proposed by Ivanenko [7, 9]. We tested the modified method on healthy subjects and then we present MN maps related to the affected and unaffected side of two post-stroke subjects.

II. MATERIALS AND METHODS

A. Protocol

Seven healthy elderly subjects (age: 63.3±3.1 ys, weight: 76.8±15.5 kg, height: 172.4±7.3 cm) who did not shown any evidence or known history of postural, skeletal or neurological diseases, and two chronic hemiplegic subjects, one left-affected and the other right-affected (Table I), were enrolled for the study. They were asked to walk on a treadmill at controlled speed of 1.1 km/h while EMG signals of 12 leg muscles (Peroneus Longus, PERL, Gastrocnemius Lateralis, GL, Soleus, SOL, Rectus Femoris, RF, Vastus Medialis, VM, Tibialis Anterior, TA, Biceps Femoris, BF, Semitendinosus, ST, Adductor Longus, ADD, Tensor Fascia Latae, TFL, Gluteus medius, Gmed, Gluteus maximum, GM) were recorded from both legs. In order to avoid as much as possible interference patterns of muscle fibers and cross talk among adjacent muscle recordings, surface electrode placement carefully followed SENIAM guidelines (www.seniam.org). Subjects donned shoes provided with foot switches in order to record heel strike events from both feet.

Inclusion criteria for hemiplegic subjects were: hemiparesis due to a single unilateral stroke and resulting in a sensorimotor disturbance of only one side, no evidence of severe cognitive or language dysfunctions that would have interfered with the ability to understand instructions, no evidence of neglect, and ability to walk without aids during experimental sessions.

The protocol was designed in accordance with the Local Ethical Committee and all participants signed an informed consent before starting experiments.

B. Data processing

Data were pre-processed (full wave rectification, zero lag low pass filtering with cut off at 10 Hz, average across gait cycles and time-interpolation over 200 points) and MN spinal cord maps related to each side have been computed in two different ways: the first one is that described by Ivanenko and colleagues [7, 9], the second one is our modified proposal.

Briefly, the activity of each spinal segment is obtained as a weighted summation of the EMG signals of those muscles innervated by each spinal section. The method proposed by Ivanenko and colleagues [7] consists in assuming weighting coefficients as 0.5 or 1, depending on the number of sources reporting the anatomical innervations of each muscle. According to the described method, it is important to remark that MN activity is estimated by using the EMG activation in an inverse like approach. In our proposal weighting coefficients are modified in order to normalize the contribution of each muscle to the MN activity of the spinal cord. This normalization is based on the fact that the EMG signal related to one muscle, is due to the contribution of all motoneurons innervating such muscle that usually are located in different spinal segments. Consequently, each EMG signal can be considered as the summation of partial contributions coming from a different spinal segment. Therefore, the activity of MN pools belonging to each segment is expected to be the summation of all EMG partial contributions related to all muscles innervated by such segment. In this regard, the traditional approach [7] tends to introduce artifacts due to an overestimation of the contribution of the EMG activity of each muscle on spinal segments innervating such muscle. Table II reports weighting coefficients according to our proposal.

TABLE I.

	Hemiplegic subjects						
	Gender	**Age**	**Weight (Kg)**	**Height (cm)**	**Affected side**	**Months elapsed from the stroke**	**Pathology**
P1	M	48	90	183	L	25	Hemorrhagic stroke
P2	M	69	72	173	R	33	Ischemic stroke

The comparisons between the two approaches have been carried out by using a 2D Correlation Coefficient.

III. RESULTS

The MN maps of healthy subjects obtained by using the original methodology were in agreement with the literature (see Fig. 1). Spinal maps were characterized by four bursts corresponding to the main phases of the gait cycle: (1) during the weight acceptance, an intensive spinal activity was located along the whole rostro-caudal segment; (2) a small activity mainly located in S2 segment occurred during the propulsion phase due to the activation of plantaflexors; (3) a moderate

TABLE II.

	Normalized Weighting Coefficients					
	L2	***L3***	***L4***	***L5***	***S1***	***S2***
GM	0	0	0	0.33	0.33	0.33
Gmed	0	0	0.33	0.33	0.33	0
TFL	0	0	0.33	0.33	0.33	0
RF	0.33	0.33	0.33	0	0	0
VM	0.33	0.33	0.33	0	0	0
ADD	0.1	0.2	0.2	0.1	0.1	0
BF	0	0	0	0.165	0.33	0.33
ST	0	0	0.125	0.25	0.25	0.25
TA	0	0	0.33	0.33	0.33	0
PERL	0	0	0.165	0.33	0.33	0
SOL	0	0	0	0.165	0.33	0.33
GL	0	0	0	0	0.5	0.5

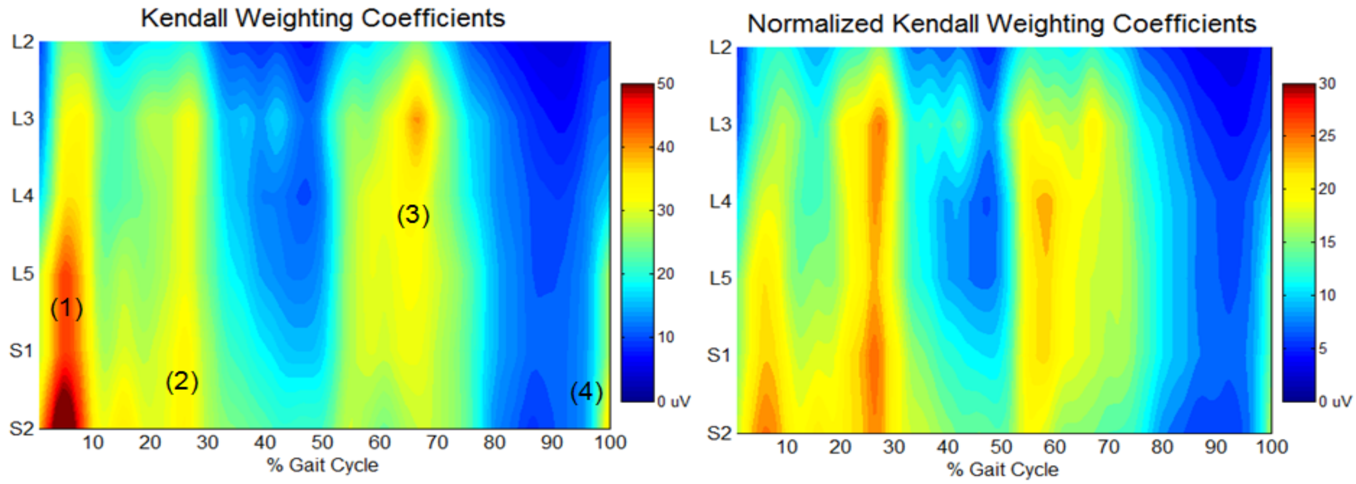

Figure 1. Representative spinal cord activity of a healthy subject (H4) estimated by using Kendall weighting coefficents, on the left, and normalized Kendall weighting coefficients, on the right. In the spinal map obtained by using Kendall weighting coefficients, the activity related to the main gait phases is marked with numbers: (1) weight acceptance, (2) propulsion phase, (3) hip flexion/ground cleareance, and (4) leg deceleration in terminal swing.

activity along L3, L4, S1 and S2 segments appeared at the beginning of the swing during hip flexion/ground clearance phase; (4) the activation of spinal segments from L5 to S2 corresponded to the activity of the knee flexors and hip extensors during terminal swing in order to decelerate leg and to prepare it to a new heel strike. As expected, due to the slow speed, MN bursts occurring during phases 1 and 2 were partially overlapped.

There were no significant differences, except for the amplitude, between spinal activity maps obtained by using the traditional method proposed by Ivanenko and our method based on normalized weighting coefficients (see Fig. 1; r=0.92±0.07). In particular, the spinal activity obtained by our method was lower, but the topography of maps remained closely comparable to those related to the traditional method.

Spinal maps of post stroke patients were dissimilar to those of healthy subjects (see Fig. 2). Moreover, in post-stroke patients, the MN activity was significantly sensitive to the observed side (Table III). In particular spinal cord activity related to the unaffected side was more intensive and spread than both the contralateral side and the activity related to healthy subjects. Reduced amplitudes characterized MN maps of the affected side. They did not present significant differences between the two hemiplegic subjects and were characterized by two main bursts before and after the heel strike.

TABLE III.

	Spinal maps of hemiplegic subjects		
	R_01	***R_0***	***R_1***
P1	-0.24	0.7±0.12	-0.15±0.15
P2	0.62	0.61±0.16	0.72±0.15

Correlation coefficients related to post-stroke subjects: R_01 is the correlation coefficient obtained by comparing spinal maps related to the affected (0) and the unaffected (1) lower limbs. R_0 and R_1 are the average spinal cord maps correlation coefficients obtained by the comparison between spinal cord map related to respectively the affected and unaffected side and the spinal cord map of each healthy subject.

IV. DISCUSSION

MN maps provide an estimation of the spatiotemporal activity of alpha motoneurons in the spinal cord during the execution of repetitive movements [7, 10, 11] and are obtained after processing superficial EMG signals. It is important to remark that they represent the relative amplitude of activity in each given spinal segment related only to the muscle activity, so they do not provide any information about the absolute amount of activity in the spinal cord. Although spinal maps are obtained by combining EMG signals and anatomical information and they represent the descending drive from spinal MNs to the peripheral muscles, they are able to provide different information than EMG signals alone. As a matter of fact EMG signals provide the results of MN spinal activity for each individual muscle, while spinal maps provide the full descending information and they are able to show an approximated representation of the organization of MN pool and the dynamic evolution of MN activation patterns during the gait cycle. Spinal maps do not represent only the peripheral information, but the output of the "spinal cord system" that integrates and processes afferent information from higher-level structures of the CNS and the sensorimotor one from the periphery.

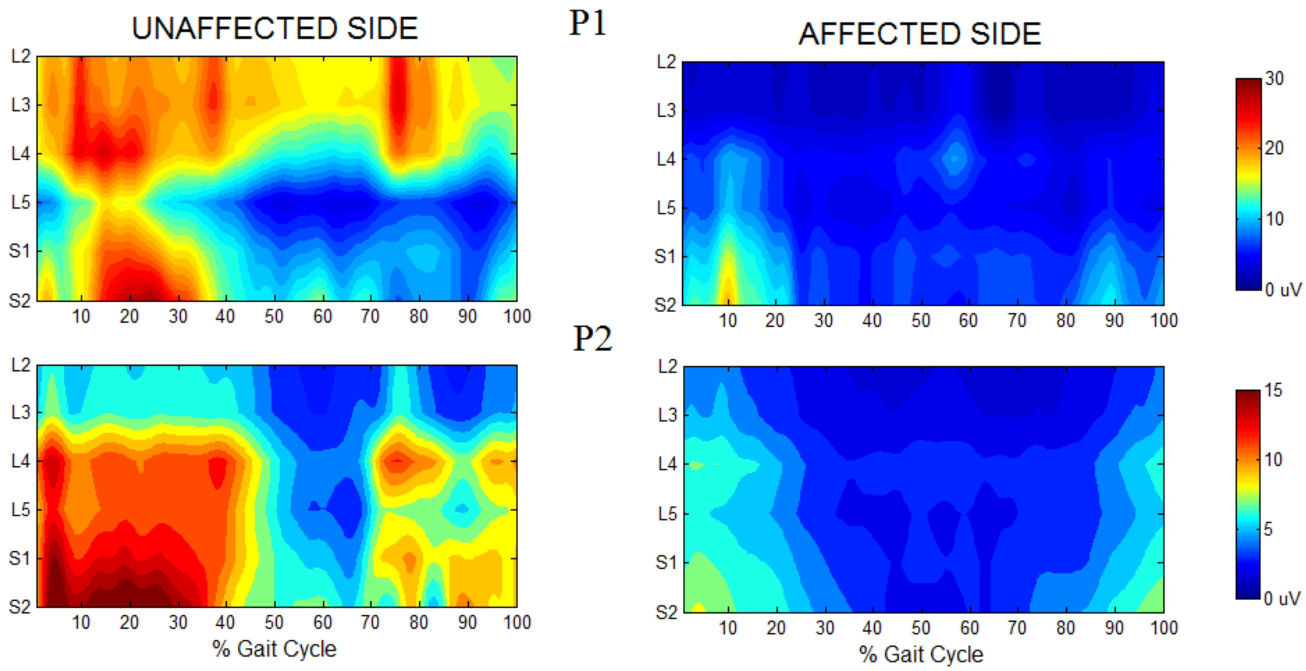

Figure 2. Spinal cord activities related to the affected and unaffected side of hemiplegic post-stroke subjects (P1 and P2) during the gait cycle. P1 was left-affected and P2 was right-affected.

In this study we suggested a modification of the weighting coefficients used to compute the MN activity, which is expected to reduce the risk of artifacts. The new weighting coefficients were obtained from the original ones taking into account that the myoelectric signal of each muscle is the sum of the activity contributions provided by several spinal cord segments.

As expected, the spinal activity obtained by this methodology is lower than that provided by the traditional one even though spinal maps estimated by both methods are significantly correlated. Therefore, both methods provide a qualitatively comparable representation of the spatio-temporal activation of MN pools belonging to the spinal cord.

This result was due to the fact that, according to Kendall's map reported by Ivanenko and colleagues [7, 13], each segment belonging to the caudal enlargement innervates 2 or 3 main muscle groups. Therefore, maps estimated by the proposed method can likely appear as a scaled version, in term of amplitude, of those obtained by the traditional approach.

From a quantitative viewpoint, results are indeed different. In particular, since main peaks and valleys can provide quantitative information concerning spatio-temporal activation of MN pools, the risk of artifacts affects in a negative fashion such estimation. Actually we have also to acknowledge that a further improvement can be achieved by normalizing EMG signals with respect to those obtained during maximum voluntary contraction. This is because, the maximum activity of each muscle, which is related to its own muscle fibers, is different among all actuators. This work represents a preliminary study in this direction and its aim is to highlight the importance of the normalization of the weighting coefficients in order to obtain a quantitative representation of MNs activity, so that spinal maps could be used as a tool which can enrich the clinical picture of subjects analyzed during walking. For this purpose an independent validation measure of this modified method is needed and it will be the object of future works.

Concerning spinal maps of hemiplegic subjects, these preliminary results show that post-stroke patients, as spinal cord injured patients [14], are characterized by both a modified MN activity compared to the healthy one, and a different inter-limb activation of MN pools.

The different MN activity of stroke patients reflects the specific redistribution of spatio-temporal activity along the spinal cord due to the pathology. In particular, MN bursts corresponding to the four temporal gait phases (weight acceptance, propulsion, flexion/ground clearance and leg deceleration) are not clearly shaped in post-stroke patients. In fact, for these subjects, spinal activity appears as consisting of two main spread bursts. From one hand, these features may be due to the reduced motor control complexity related to the pathology [15]. From the other, it is possible to suppose that the spread activity of MN pools in the unaffected side versus a quite silent activity related to the affected side can reflect the inter-hemispheric coordination which is influenced by the stroke.

V. CONCLUSIONS

Spinal maps represent a good method to evaluate MN activity during the execution of repetitive and cyclic motor tasks, such as walking, also in subjects who experimented a stroke, and it could be a simple method to monitor the output state and plasticity of the neural network in the course of recovery of locomotion in these patients. In this regard, spinal maps could be used to study the evolution of the MN pool activation patterns among spinal cord segments in order to assess whether rehabilitation treatments are effective in promoting a redistribution of the MN activity and therefore the plasticity of the central nervous system.

This preliminary study of spinal activity in two post-stroke subjects shows a redistribution of spatiotemporal activity and a reduction of the main spread bursts of activity underlying the reduced complexity of the motor control.

An improvement of the quantitative information provided by this methodology must be done in order to make it a suitable tool for the assessment of walking capability in a clinical context.

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